Chapter

Wax Deposition in Crude Oil Transport Lines and Wax Estimation Methods

Fadi Alnaimat, Mohammed Ziauddin and Bobby Mathew

Abstract

Petroleum industry is one of the major industries serving the energy demands. Flow assurance is essential for providing continuous fuel supply. Wax deposition is the main issue that affects flow assurance or reduces the efficiency of transporting crude oil. As the maintenance cost of repairing and troubleshooting is very high, addressing issues related to flow assurance becomes critical in the petroleum industry. This chapter will explore methods used for reducing, cleaning, and monitoring deposition of wax. Wax dissolved in the crude oil gets crystallized causing accumulation across the pipe walls once the bulk temperature of the crude oil gets lower than wax appearance temperature (WAT). Mechanical, thermal, chemical, and microbial methods highlighting general practice in the industry are discussed in this chapter. Next, the direct techniques providing information about the numerical wax deposition models used along with scientific measurement techniques are emphasized. Later, the indirect measurement techniques are discussed providing information about the external probing and nondestructive techniques to obtain information about wax layer deposition inside the pipe. The role of artificial intelligence and use of fuzzy logic for effective wax prediction or in developing the existing wax numerical models are emphasized in the last section.

Keywords: wax deposition, numerical model, wax appearance temperature, artificial intelligence, fuzzy logic

1. Introduction

Energy demands are continuously fulfilled by the petroleum industry. Transport lines of crude oil play an essential role in ensuring continuous supply of fuel, that is, providing flow assurance. As the maintenance cost of repairing and troubleshooting transport lines is very high, addressing issues related to flow assurance becomes critical in the petroleum industry. Crude oil consists of wax particles that are initially in the dissolved state and those get crystallized once the temperature of the pipe wall goes below certain temperature. The wax content in the crude oil is firstly in the dissolved form, and then it gets to precipitation and then gets crystallized causing accumulation across the pipe walls. This process is explained by molecular diffusion of wax particles toward the pipe wall when the temperature of the crude oil in bulk gets lower than wax appearance temperature (WAT) [1–8].

Wax deposition is a serious problem that causes reduction in the flow cross section, hence affecting flow assurance. In the subsea transport lines, the surrounding temperature drops very low which increases the crystallization, and wax deposition becomes more acute (as shown in **Figure 1**). With time, the crystallized wax particles get accumulated layer by layer and even can clog the pipe completely, which dramatically affect the maintenance work. Therefore, there are many methods used and studied by the industry as well research and development institutions in this direction to effectively find out the location of clog, to minimize the issue deposited wax, to remove the deposited layer of wax, and to predict the wax deposition inside the transport lines with time. All these efforts are taken to reduce wax deposition and mitigate in such a way that wax layer thickness can be predicted and addressed for maintenance once it reaches to a caution limit. Hence, predicting wax deposition can help in preventive maintenance and cost-effectiveness [9–13, 16].

This book chapter will discuss methods which are used for wax clearance, prediction, and estimation. This book chapter will cover mainly four sections: introduction, wax deposition issues and solutions, wax estimation methods, and role of artificial intelligence in wax prediction. The first section introduces the basic theory behind the wax deposition as a process and explains the main factors that are affecting wax deposition. The second section discusses four different methods adopted to tackle the problems related to wax deposition. The four different methods, mechanical, thermal, chemical, and microbial methods, will be discussed highlighting general practice in the industry. Further, their advantages and limitations are added in the same section. The third section is consisting of broad discussion which includes comparison of direct and indirect measurement techniques. The direct techniques are highlighting information about the numerical wax deposition models used along with scientific measurement techniques. On the other hand, the indirect measurement techniques are discussed knowing the external probing and examining techniques that can provide information about wax layer deposition inside the pipe. Finally, the role of artificial intelligence is discussed with benefits associated with the use of mapping information and using fuzzy logic for effective wax prediction or in developing the existing wax numerical models. Lastly, a brief conclusion is provided to reflect recent literature and hot topics in this direction.
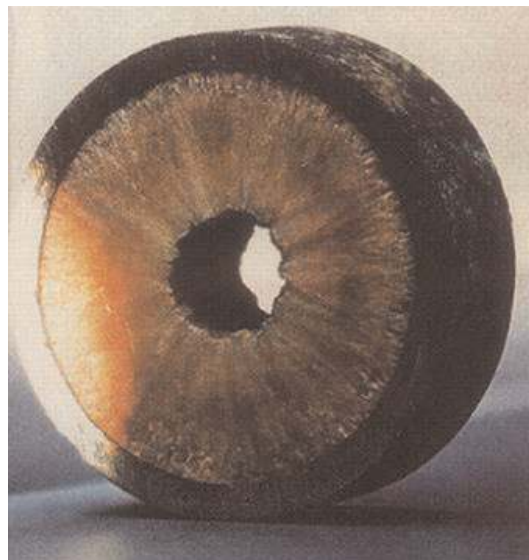

Figure 1.
Sectional view of pipeline affected with acute wax deposition [14].

2. Wax deposition issues and solutions

The issue of wax accumulation is complex because many factors affect the wax deposition such as the wax concentration in crude oil, temperature of the surrounding, wax appearance temperature, pressure drop, viscosity of the oil, and bulk temperature of the oil. The main associated issues with wax deposition in crude oil transport lines are impact on flow assurance and a sudden clog that can lead to immediate actions of maintenance and repair. Deposited layer of wax can be observed as three sub-layers: the topmost layer is more granular and soft, the bottom layer is observed to have a strong bond with pipe wall and considered as close fitted layer, and the sandwiched layer in between the top and bottom has the mechanical impurities and high wax content. With time, the sedimented layers get hard and move from top layer stage to bottom layer stage, consequently reducing the effective flow cross section. The process of hardening of the bottom sedimented layer of wax is referred to as "aging." Hence, it is crucial to understand that with time, the wax deposition can cause difficulty in the cleaning process [11–13, 16–22].

To deal with wax deposition issues, conventionally in the industry, pigging process is used for cleaning the wax after inspecting externally or cleaning as a part of regular maintenance. In the pigging process (as shown in **Figure 2**), the deposited wax is scrapped by passing the pig device through the pipe such that its movement along the pipe causes its head to collect the deposited layer of wax. However, the pig device inserted has possibility to get stuck due to hard layer of wax or due to higher friction from the accumulated wax when cleaning longer distances. If the pig device gets stuck in between the pipe not near to inlet or outlet connections, then it becomes a hectic and complex issue to deal. In the following sections, common methods (mechanical, thermal, chemical, and microbial) are discussed in dealing with issues related wax deposition [16–22].

2.1 Mechanical methods

Mechanical removal of wax is considered as the oldest method used in the industry. This method includes the use of scrappers directly, use of scrappers in the tube, and use of "pig" device inside the pipe. Scrappers are used to scrap the tube wall and remove wax even when the well is under operation. Pipeline inspection gauge (pig) device is one of the broadly used old methods that have been used since a century in the industry [16–22].
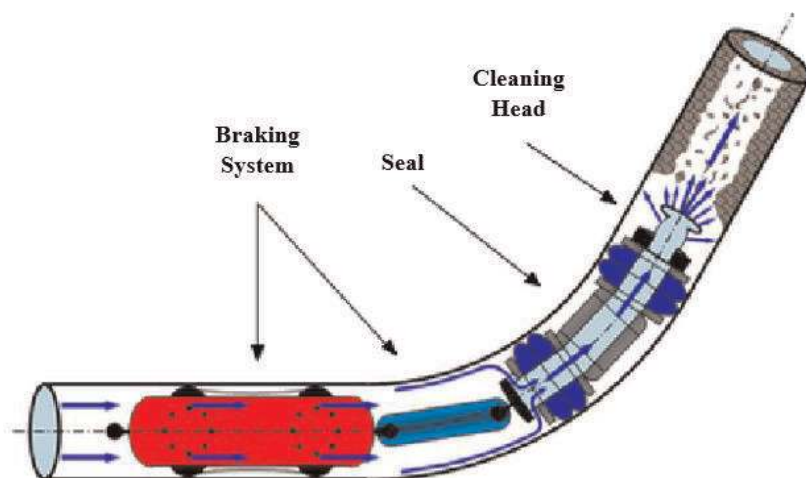

Figure 2.
Pigging process [15].

Both wax removal techniques are used for maintenance; however, they have disadvantages of plugging of perforation within the well when scrapping and when the pigging device gets stuck inside due to wax. All the mechanical methods are economical in comparison to other methods [16–22].

2.2 Thermal methods

Thermal methods are basically used to adhere to temperature medium or maintain temperature of crude oil for reducing wax buildup. Some of the common ways used are hot oiling or hot watering, cold flow, and surface coating. Using hot oil or hot water (temperature in range 65–105°C) pumping in the transport line, the deposited wax is melted. Using solid resin particles that are having melting point more than WAT in the oil facilitating slurry flow, the wax is prevented to deposit toward the wall. Using surface coating of thermal insulation material (like plastic), the wax inhibition is achieved shielding the drop of crude oil temperature. All these methods can be used; however, there is limitation of using hot oil or hot water depending on the heat capacity of the oil [16–22].

2.3 Chemical methods

Chemical methods are basically using chemical inhibitors, and these are added in the oil to reduce the wax deposition. These chemical wax inhibitors can be classified into three: detergents, dispersants, and wax crystal modifiers. Surface activators are the detergents and dispersants that sustain wax particles as suspended and dispersed such that reducing the wax particles to adhere to each other or the pipe walls or any solid surface. The surface activation agents also modify the solid surface of the pipe reducing shear and interaction of wax particles on the wall of the transport line. Other types of surfactants also modify the solubility by solubilizing nucleus and avert agglomeration of wax particles. Wax crystal modifiers are also referred to as pour point depressors because they allow the flow of oil at a minimum temperature at its own density and given conditions. Wax crystal modifiers have same structure as that of the wax particle, and they coprecipitate occupying on the crystal lattice of wax particle forming hydrocarbon chains. In this manner, they also act as encumber in the growth of wax crystals as they reduce the possibility of wax crystals to form 3D structures. All these wax inhibitors are effective but must be used before crude oil bulk temperature is above its WAT [16–22].

2.4 Microbial methods

Microbial method of treating wax is not common; however, it was found effective in few field testings. The action of bacterial culture is producing the biosurfactant which is reported to facilitate as wax inhibitor. The bacterial strains such as *Actinomyces* species have shown breakdown of heavy chain hydrocarbon fractions (from C_{15} to C_{20}) when treating the crude oil samples. Bacterial treatment was also noticed to induce crude oil lowering the WAT of the crude oil. This makes the crude oil with less susceptible condition for wax deposition. Using microbial method is an innovative approach, but it could be used in wells to have static culture [16–22].

3. Need for mitigation and wax estimation methods

Methods discussed earlier including mechanical, thermal, chemical, and microbial methods were to reduce and clean the wax deposited inside the transport lines.

Those methods served as the final solution for cleaning. However, as a part of mitigation and carrying out preventive maintenance, there is a need to have methods that can serve for estimating the wax buildup. This section is focused toward discussion of methods that can help in wax estimation. The direct measurement techniques are discussed to show the benefits associated with information process and about the numerical wax deposition models used along with scientific measurement techniques. The indirect measurement techniques are discussed to show how nondestructive testing can provide information through external probing and examining externally to know about wax layer deposition inside the pipe. Hence, this section is critically for knowing how the estimation is carried out regarding the wax layer thickness inside the crude oil transport line. Further, these are significant in avoiding sudden shutdowns due to blockage or complete closure with wax inside the pipe which can result in immediate maintenance cost [23].

3.1 Direct measurement techniques

Direct measurement techniques help in estimating the deposited wax layer thickness based on numerical assessment of deposition models as mentioned in the literature. The information about the parameters that are added to the model dependent on wax properties are measured using scientific measurement techniques. In other words, the estimation of the deposited wax layer is through wax deposition model but coupled with output obtained from scientific measurement. This section explains various wax deposition models highlighted in the literature and pointing out the most suitable model based on the assessment. In addition, different scientific measurement techniques are explained with respect to capability of each technique based on properties measured [23].

3.1.1 Wax deposition models

Mathematical modeling approach is widely adopted in order to predict and monitor wax deposition either through numerical estimation directly or using software that has back-end mathematical model. In this section, some of the main highlighted wax deposition models from the literature are discussed along with respective equations. Wax deposition models are developed based on consideration of assumptions and selection of parameters. Four main models are discussed in this
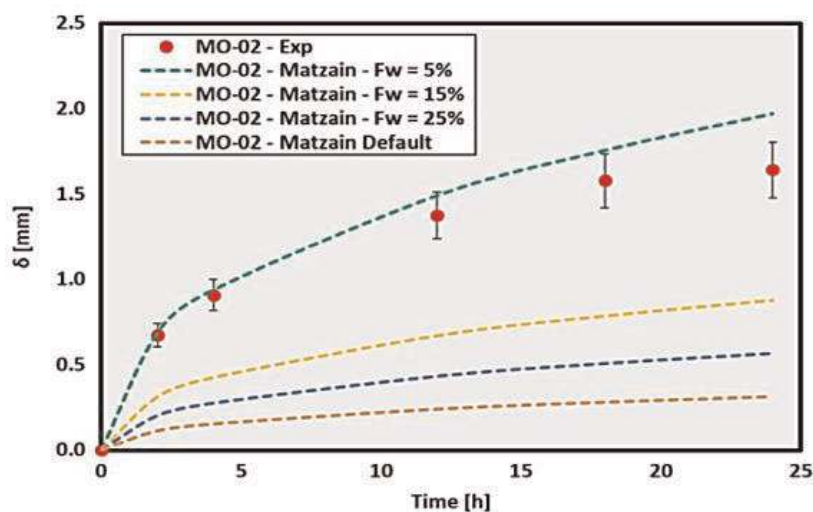

Figure 3.
Matzain's model comparison to experimental results [28].

book chapter: film mass transfer model (FMTM), equilibrium model (EM), Matzain's model (MM), and Venkatesan's model (VM) [24–28].

FMTM is developed based on the mass and heat transfer assumptions considering both transfers occur independently. EM is developed based on thermodynamic equilibrium along with consideration of concentration gradient in the model unlike FMTM. MM is a modified model of EM making it more effective by including the diffusion equation as empirical correlation as well as including the factors related to shear stripping and trapped oil factors. VM is developed mainly considering shear effect with two coefficients along with quantification of mass flux in the model [23, 29–36].

Among these four models, MM was found to be self-sufficient due to its fitting with experimental data. Also, it was due to consideration of oil entrapment and correlation of hear stripping effect in the model. The results obtained by testing MM model are shown in **Figure 3** [23, 29–36].

The mathematical equations governing with respect to all these four models are mentioned below [23, 29–36]:

$$k_L.2\pi r_i L\left[C_b - C_i(T_i)\right] = D_e(2\pi r_i L)\frac{dC}{dT}\bigg|_{T_i}\frac{dT}{dr}\bigg|_{r_i}^+ + -\frac{d\left(\pi r_i^2\right)}{dt}\rho_w.L.\overline{F_w} \tag{1}$$

$$D_e = \frac{D_{wo}}{1 + \alpha^2 \frac{\overline{F_w}}{(1-\overline{F_w})}} \tag{2}$$

$$\alpha = 1 + K_\alpha.\overline{F_w} \tag{3}$$

where k_L is the convective mass transfer coefficient, D_{wo} is the diffusivity coefficient, F_w is the wax fraction percentage, C_b is the bulk soluble wax concentration, C_i is the interface soluble wax concentration, ρ_w is the wax density, α is the wax crystal aspect ratio, and K_α is the aspect ratio proportionality constant. K_α is used as fitting parameter [23, 29–36]:

$$D_{wo}.(2\pi r_i L)\frac{dC}{dT}\bigg|_{T_i}\frac{dT}{dr}\bigg|_{r_i}^- = D_e(2\pi r_i L)\frac{dC}{dT}\bigg|_{T_i}\frac{dT}{dr}\bigg|_{r_i}^+ + -\frac{d\left(\pi r_i^2\right)}{dt}\rho_w.L.\overline{F_w} \tag{4}$$

$$\frac{d\delta}{dt} = -\frac{\pi_1}{1 + \pi_2}\frac{D_{wo}}{\rho_o}\left[\frac{dC}{dT}\bigg|_{T_i}\frac{dT}{dr}\bigg|_{r_i}^+\right]$$

$$\pi_1 = \frac{15.0}{1 - C_{Oil}/100} \tag{5}$$

$$\pi_2 = 1 + 0.055\,N_{SR}^{1.4} \tag{6}$$

$$C_{Oil} = 100\left(1 - \frac{R_e^{0.15}}{8}\right) \tag{7}$$

$$N_{SR} = \frac{\rho_o v_o \delta}{\mu_o} \tag{8}$$

where δ is the thickness of deposited wax, ρ_o is the density of the oil, μ_o is the viscosity of the oil, N_{RE} is the Reynolds number, N_{SR} is the dimensionless shear number in Matzain's correlation, C_{Oil} is the trapped oil coefficient, and π_1 and π_2 are the Matzain's empirical coefficients 1 and 2, respectively [23, 29–36]:

$$\dot{m}_w = k_L.2\pi r_i L\left[C_b - C_i(T_i)\right] - m\,\tau_W^n \tag{9}$$

where $\dot{m}_w$ is the rate of molecular weight of deposited wax; coefficients m and n are 0.8 x 10^{-12} and 1.9, respectively; and τ_W is the wall shear stress [23, 29–36].

3.1.2 Scientific measurement techniques

Scientific measurement techniques are coupled to wax deposition models practically because these techniques assist in providing information that is necessarily required as inputs for providing the output which is predicting the wax deposition thickness. Most dominating measurement techniques used in the industry for obtaining properties of crude oil samples are discussed here, which include near-infrared scattering (NIR), small-angle X-ray scattering (SAXS), X-ray diffraction (XRD), controlled stress rheometer (CSR), and cross-polarized microscope (CPM) [23].

3.1.2.1 Near-infrared scattering (NIR)

NIR is using the property of light scattering considered in a colloidal solution and obtains the physical properties. The near-IR range wavelength (low IR wavelength) attenuation spectra provide accurate results for obtaining WAT. The measurement deviation of ±2.5°C is observed when comparing the results obtained by CPM. This technique is effective with high-resolution results analyzed in 55 nm size window. It is also applicable if the oil sample is almost opaque to find out the WAT through delineation of radiation attenuation [37].

3.1.2.2 Small-angle X-ray scattering (SAXS)

Investigations carried out studying SAXS help in obtaining the radii of gyration. This technique can be used to study different fractions of crude oil at different operation temperatures. X-ray scattering at small angle can have issues related to low intensity. SAXS experimental results can be compared to calculations of scattering length density using chemical composition. This technique is applicable to obtain the size from radius of gyration and power law exponents providing details about physical properties of the crude oil sample [38–45].

3.1.2.3 X-ray diffraction (XRD)

This diffraction technique provides information about the crystal size of the wax by scattering in the time domain. XRD can help in understanding the wax structure capturing the wax deposition and aging. When using XRD it is important to understand that crystal size can also affect the diffraction. When the size of the crystal is below 0.1 μm, broadening of the diffraction peaks can be observed, and this broadening is as twice of the given angle. However, when the size of the crystal is above 0.1 μm, the diffraction characterizes Darwin width the same as the given angle of diffraction. XRD is suitable for characterizing crude oil samples studying the solid-solid transitions; hence, this method is effective in determining the crystal structure. But XRD has limitations in understanding the liquid-solid equilibrium, that is, identifying the crystallization from liquid to solid [46–50].

3.1.2.4 Controlled stress rheometer (CSR)

This technique utilizes the application of controlled stress on the sample with arrangement of parallel plate to obtain the strain exerted. In this manner, steady

stress and steady deformation are obtained, and measurement of viscoelastic properties of the wax sample is achieved. For measurement, it is important to make sure that two parallel plates are set properly. The difficult part in measurement is that during measurement and when applying stress, it is crucial to make sure that the top layer does not slip. Slippage can affect the results, and when the wax weight percent is above 5%, slippage can be more prevailing when taking measurement [51–56].

3.1.2.5 Cross-polarized microscopy (CPM)

When analyzing the impact of cooling on the crude oil microstructure, CPM can be used. It can help in measuring WAT because cooling rate provided to the crude oil sample can be controlled and morphology can be observed with time. CPM provides information about the wax precipitation as wax appearance can be noticed with high resolution in small-size dimensions up to 0.5 μm. The volume of the sample stored for testing is very small, and CPM is sensitive to film thickness of sample which is dependent on the concentration of the sample [57–64].

3.2 Indirect measurement techniques

Indirect measurements here are referred to techniques which are evaluating the wax deposition experimentally by assessing physical quantities such as volume, temperature, pressure, electric capacitance, and ultrasonic signals. Change in volume is evaluated such that the resulted difference is the volume fraction of deposited wax. Similarly, the difference in pressure is also considered accounting for deposited wax. Both methods are intrusive, hence limiting its application in the industry. Therefore, nondestructive techniques are to interest which includes techniques that use temperature sensing, electrical capacitance measurement, and ultrasonic assessment [23]. Firstly, applying the temperature-based techniques, thermal sensing utilizes the heating pulse applied externally, and its transient response can assist in real-time assessment and monitoring of wax deposition [65, 66]. The investigation by [67] collected information about wax thickness inside the transport pipeline by observing the acoustic signals after providing the heat pulse externally. Signals obtained were Fourier transformed to observe frequency domain and extract information correlating to deposited wax layer thickness. Secondly, electrical capacitance measurement widely known in the literature as electric capacitance tomography (ECT) is effective in providing high-quality images by applying complex algorithms. ECT examined on the nonmetallic transport pipe experimentally showed that online monitoring of wax deposition can be achieved. Thirdly, ultrasonic measurement technique is also applied externally, and the information provided by the decaying time of ultrasonic signals can be correlated to deposited thickness of wax. Overall, many investigations are in the direction of exploring capabilities of ECT; however, few studies focused on nondestructive testing related to temperature-based prediction and related to ultrasonic decay time measurements [68–70].

4. Role of artificial intelligence

The trend of research and development in the oil and gas industry is shifting toward utilization of artificial intelligence (AI) algorithms and machine learning concepts. Based on the respective operating conditions, making the systems equipped with AI can enhance the decision-making capabilities. Some of the

commonly used AI algorithms are evolutionary algorithm (EA), artificial neural network (ANN), swarm intelligence (SI), and fuzzy logic (FL). More than one AI algorithm can be applied if needed. Adaptive Neural Fuzzy Inference System (ANFIS) provided information about best has condensation ratios using ANN and FL assessment helped in continuous optimization of wax deposition model [23]. Among the recent studies, the work of [71] used statistical model considering the dependent and independent variables for wax deposition prediction. The dependent variable considered is viscosity of the crude oil, whereas the independent variable considered is pressure. By plotting pressure/viscosity versus pressure plot (as shown in **Figure 4**), the linear boundary limits were kept, and if the actual plot goes above the upper limit, it implicates high potential of wax deposition. The ANN model was developed based on backpropagation neural network (BNN). BNN uses two loops, a forward and a backward loop. The forward loop helps in processing the information inputs to outputs, whereas the backward loop does opposite from output to input. The backward loop processes information along with the weight error correction to take as input to forward loop. In the manner, the continuous operation of forward to backward and backward to forward loops, backpropagation algorithm gets trained. Hence, BNN is also referred as learning algorithm due its adjusting weights confined in the neural network.

More concise modeling is observed from work of [72] which consisted of ANN mathematical model for predicting rate of wax deposition. After observing that deposition rate of wax experimentally to be nonlinear, Kolmogorov theorem was applied; it virtually approximates nonlinear function to linear using two-layer ANN with certain error limit. The mapping structure for predicting wax deposition rate is shown below in **Figure 5**. The input variables (viscosity, shear stress, temperature gradient, and concentration gradient) and output variable is wax deposition rate. Comparison of the results with determined set showed that linear regression model was having correlation of 0.78, whereas ANN model had 0.97.

The work of [73] used ANFIS model to predict thickness of deposited layer of wax considering single-phase turbulent flow. Five-layered ANFIS model was considered consisting of input variable as Reynolds number, wax concentration (%), time, temperatures (outside, inside, and pipe wall), and temperature-driven force
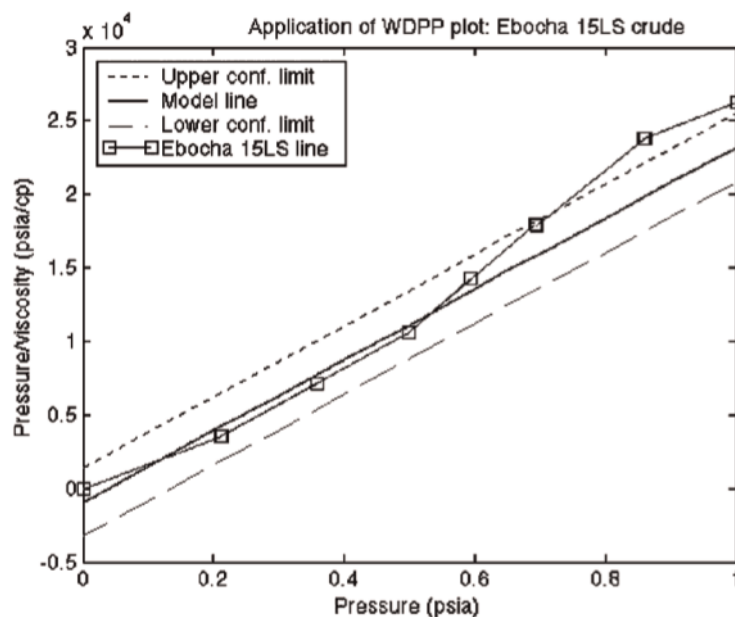

Figure 4.
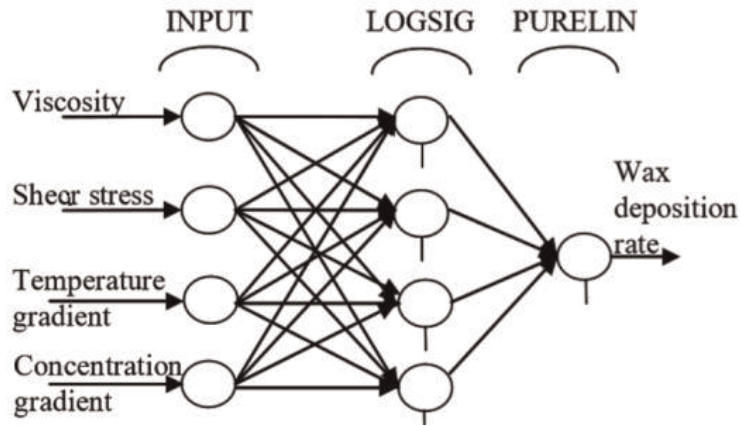*Prediction of potential to wax deposition [71].*

Figure 5.
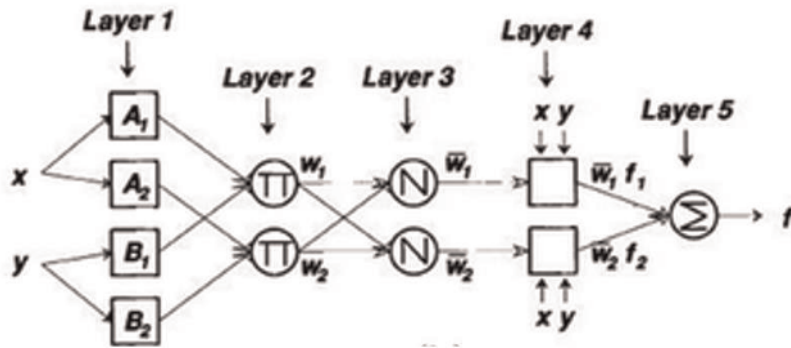*Structure of ANN model for wax deposition rate prediction [72].*

Figure 6.
Structure of ANFIS model for wax thickness prediction [73].

(ratio of gradient temperature wall and outside to bulk temperature of the oil). As shown in the **Figure 6**, the ANIFS model has five layers, and respective equations governing output of the model are mentioned below. The first-order fuzzy logic is applied using if/then rule. Considering if "A_i" belongs to "x" and "B_i" belongs to "y," then "f_i" the output function can be represented with combination of the parameters ("p_i," "q_i," and "r_i"):

$$f_i = p_i x + q_i y + r_i (i = 1, 2, ..., n) \tag{10}$$

In the first-layer equation representation, the combination can be calculated as its membership degree (μ) for labels set "A_i" and "B_i":

$$O_i^1 = \mu_{A_i}(x) \quad and \quad O_i^1 = \mu_{B_i}(y) \ (i = 1, 2, ..., n) \tag{11}$$

In the second-layer equation representation, it can be shown with product of the membership degrees:

$$O_i^2 = W_i = \mu_{A_i}(x) * \mu_{B_i}(y) \qquad (i = 1, 2, ..., n) \tag{12}$$

In the third-layer equation representation, the calculation of the weighted ratio from each variable with respect to total weight is

$$O_i^3 = \overline{w_i} = \frac{w_i}{\sum_{i=1}^{n} w_i} \qquad (i = 1, 2, ..., n) \tag{13}$$

In the fourth layer equation representation, the adaption is achieved at this layer identifying this layer as defuzzification layer, where the learning rule is applied on this layer (i.e., minimizing the error). The summation of the weight applied with function is a resultant referring to the output layer, which is the fifth layer:

$$O_i^4 = \overline{w_i} f_i = \overline{w_i} \left(p_i x + q_i y + r_i \right) \qquad (i = 1, 2, ..., n) \tag{14}$$

$$O_i^5 = \sum_{i=1}^{n} \overline{w_i} f_i \qquad (i = 1, 2, ..., n) \tag{15}$$

The prediction of the deposited thickness of wax using this model resulted in close agreement with experimental values. The mean square error values comparing to experimental results was to three digit accuracy (0.00077034) and high value of correlation (0.9858).

5. Conclusions

In brief, this chapter explores different methods used in the industry and research for predicting and monitoring wax deposition. The information discussed introduces the process of wax deposition and wax deposition models as a theoretical background. Observing the recent literature, the role of artificial intelligence is discussed which is to serve in effective and precise prediction of wax deposition. Hence, artificial intelligence for application of nondestructive data collection assessment helps in developing the wax deposition models to incorporate the updated oil sample information periodically to ensure that the wax predictions are reliable.

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Conflict of interest

The authors have no conflict of interest.

Notes/thanks/other declarations

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Author details

Fadi Alnaimat*, Mohammed Ziauddin and Bobby Mathew
United Arab Emirates University, Al Ain, United Arab Emirates

*Address all correspondence to: falnaimat@uaeu.ac.ae

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